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16. Abstract

A technique is proposed for quantifying the amount of energy released when synthetic lines fail and recoil, called snapback. Ten synthetic line material/construction combinations are investigated by bending the line around a 1" diameter pin fixture and loading until failure occurs at the pin. High-speed photography is used to calculate the velocity of the line at failure and the attending kinetic energy. Three parameters are proposed to quantify snapback; (a) the Storage Energy Potential is a measure of how much energy a line stores as load is applied to it, (b) Snapback Energy Potential is a measure of the kinetic energy that the line possesses after failure occurs and the line recoils, and (c) the Energy Release Ratio indicates the proportion of stored energy that becomes kinetic energy after the line parts.

In addition to discussing the evaluation technique, the various lines tested are compared to determine if some materials or constructions have a lower potential to snapback.

The failure mechanism (i.e., the sequence of yarn failures that culminate in complete failure) of each line construction is observed using high-speed photography to determine if lines with a cascading failure mechanism (i.e., failure over a relatively long period of time) have lower snapback potential.

The path that a line follows during snapback is also observed. Lines snap back directly toward the fixed end if the failure occurs in clear line. If a line retracts around the curved surface such as a bollard, significant lateral velocity is imparted to the line and it sweeps a wide area.

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METRIC CONVERSION FACTORS

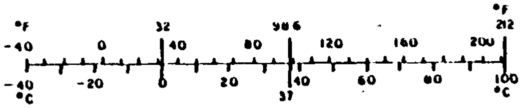
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 BACKGROUND AND OBJECTIVES

The potential of personnel injury and equipment damage by parting synthetic lines under tension, referred to as snapback, is drawing attention in a variety of fields. The Agricultural Engineering Department at Cornell University is investigating snapback because of the potential injury and damage caused by synthetic lines used to pull farm equipment out of ditches. Hawkins and Tipson Ropemakers, Ltd. in England is developing a low snapback line for the West German and United Kingdom armies to free stranded vehicles. A similar awareness of the potential danger of synthetic lines has prompted increased activities in the U. S. armed services. The U.S. Naval Oceanographic R&D Activity, under the sponsorship of the Naval Sea Systems Command, is developing a low snapback line for docking ships. Accidents caused by parting lines during mooring and towing operations on U.S. Coast Guard and Navy ships caused four deaths, four amputations, and a variety of injuries in the latter half of 1980. An incomplete survey of just U.S. Coast Guard synthetic line accidents over the past seven years has shown an average of 10.7 accidents per year with 135.3 staff days of lost work. In response to these accidents, the Ocean Engineering Division of the Coast Guard and the Naval Sea Systems Command (NAVSEA) initiated a joint project to investigate the snapback phenomena; the work in this report was undertaken to support this joint project.

The primary objective of this investigation is the quantification and characterization of snapback so that commercially available synthetic lines can be evaluated and compared for snapback potential. It is also possible that the insights gained might be of use in developing new lines that have improved snapback properties. To meet the objectives of this study, laboratory experiments were conducted in the Synthetic Line Laboratory at the U.S. Coast Guard Research and Development Center to observe lines as they fail and measure the kinetic energy of a line as it retracts. The snapback quantification techniques developed, as well as the laboratory experience and insights gained, will provide guidance for future experimentation on configurations that simulate operational circumstances.

2.0 SUMMARY

Three parameters are proposed to quantify the snapback behavior of synthetic lines. The Storage Energy Potential is a measure of how much energy a line stores as load is applied to it; the Snapback Energy Potential is a measure of the energy that a line possesses after failure occurs and the line recoils; the Energy Release Ratio indicates the proportion of stored energy that becomes kinetic energy after the line parts. Ten synthetic line material/construction combinations are investigated by bending the line around a pin fixture (1-inch diameter) and loading until failure occurs at the pin. High-speed photography is used to calculate the velocity immediately after failure and the attending kinetic energy. Lines are then compared by use of the Storage Energy Potential, Snapback Energy Potential, and the Energy Release Ratio. This data is compared to limited amounts of data from similar investigations.

The Storage Energy Potential is fundamental to a line material/construction combination and is independent of diameter. The Storage Energy Potential varies over a range of about 100% for the lines tested.

The Snapback Energy Potential of 8-strand plaited line is only slightly greater than that of double-braid line; the Snapback Energy Potential of nylon line is 60% higher than polyester line. Nylon cross-lay line and polyester double-braid line have Snapback Energy Potentials that are as much as 50% lower than the other lines tested.

The Energy Release Ratio varies with material and construction, however, no trend is apparent. Nylon cross-lay and polyester double-braid lines have Energy Release Ratios that are approximately 50% lower than the other lines tested.

Nylon cross-lay line exhibits a cascading failure mechanism and has a correspondingly lower Energy Release Ratio. Nylon cross-lay line fails in 5-7 milliseconds whereas double-braid and 8-strand plaited constructions (of either nylon or polyester) fail almost one order of magnitude faster. Polypropylene 8-strand twisted staple fiber line also appears to fail in a cascading fashion. However, limited data is available because that line does not consistently fail completely when loaded around the pin fixture in the lengths used in the laboratory.

Lines snap back directly toward the fixed end if the failure occurs in clear line. If the line retracts around a curved surface such as a bollard, significant lateral velocity is imparted to the line and it sweeps a wide area.

Snapback velocity for a particular material/construction combination is independent of diameter and dependent on the tension at failure. The velocity of the line is not constant over the length; the highest velocities occur at the fractured end and decrease away from that point. The theoretical snapback velocity (calculated by assuming that all stored energy is converted to kinetic energy after failure) is between 8% and 69% higher than the actual measured velocity.

Snapback data is generally not available for three-strand lines because it does not fail completely when loaded around the pin fixture.

3.0 GENERAL TECHNICAL APPROACH

3.1 Background

Two previous studies investigated the snapback behavior of synthetic lines. Portions of these studies furnish some background information and provide a point of departure for this investigation.

Wesler and Parker (Reference 1), at the U.S. Coast Guard Field Testing and Development Center, investigated snapback in a large number of synthetic lines used in small boat towing operations. The testing was intended to simulate the failure of deck fixtures during towing operations. Several key points limit the direct application of that data to this study. First, the lines were loaded to a high percentage of the tensile strength and then released with a pelican hook. The line does not fail catastrophically in this method and any energy dissipation attributed to the characteristic manner in which line construction failure occurs is not observed. Second, a shackle was placed on the end of the line and released with the line. This simulates an all-too-common situation in which the cleat on the deck of a pleasure boat being towed is pulled from the deck and propelled at the towing vessel by the stored energy in the line. This complicates the comparison of that data with other data. Data from Wesler and Parker's study does indicate that kinetic energy is approximately a linear function of tension. This lends additional validity to the analysis techniques used in this study.

Dr. Feyrer (Reference 2), at the University of Stuttgart, conducted a snapback investigation in which the kinetic energy of a variety of Kevlar, wire and conventional synthetic lines was measured. The general testing technique developed by Dr. Feyrer was adapted for this investigation. One of the important results of that investigation is the importance of the line construction on snapback. Some constructions, such as wire rope, show a cascading failure mechanism which allows some energy to be dissipated before complete failure occurs; this results in less snapback. Neither the Feyrer tests nor the Wesler and Parker test results address the question of snapback path. The data from both investigations does tend to indicate that lines that fail in clear line recoil with very little sideways motion. Some of the data from the Feyrer tests (Reference 2) are used to directly complement the analysis in this study and some of it is used only to substantiate trends in data.

3.2 Definition of Terms

The investigation of snapback is made more difficult by its very nature - it is an unexpected, unpredicted accident when it happens. In order to study it, the elements of the problem must be separated, understood and simulated in a controlled setting in which measurements and observations are taken. Establishing definitions is a useful introduction to the detailed technical approach:

a. Storage Energy - Storage Energy is the energy that is stored in a line during loading. Graphically, it is the area under the load-elongation curve.

b. Snapback Energy - Snapback Energy is the energy that is expended by the line as it recoils after failing completely. Kinetic energy is used in this investigation to represent the snapback potential of the line.

c. Energy Release Ratio - Energy Release Ratio is the ratio of the snapback energy to the stored energy. It indicates what percentage of the energy that goes into a line during loading (i.e., potential energy) is released as kinetic energy after the line fails completely.

d. Failure Mechanism - Failure Mechanism describes the sequence of yarn failures that culminate in complete failure of the line or at least a subsequent reduction in load-carrying capability.

e. Failure Time - Failure Time is the time between the beginning of the failure mechanism (i.e., incipient failure) and complete failure or parting of the line. It is the time period during which some stored energy may be dissipated before the line fails completely.

4.0 EXPERIMENTAL PLAN

4.1 Background

The failure caused in the laboratory must be similar to that occurring in the field. The point of failure of a line in a field situation is a function of such factors as local line damage and stress risers caused by bending the line around hardware such as bollards and fairleads. Since synthetic line failures are accidents, location and instant of failure are usually not known. In order to observe the recoiling line, measure kinetic energy and observe the failure mechanism, a method must be selected that causes predictable line failure with minimum disruption of the failure mechanism. In his snapback work, Professor Feyrer (Reference 2) bent a line around a small diameter pin to create a point of elevated stress at which failure occurred. This method seems to work adequately and was subsequently adopted for this investigation. This method of failure initiation is also compatible with the primary data collection technique used in this investigation, that is, high-speed photography. Bending a line around a small-diameter pin provides (a) a repeatable load to key the high-speed cameras, and (b) a known failure point to train the camera on for a close-up observation of the failure mechanism. The line sample length in this investigation is limited by the length of the testing machine frame and the stroke of the hydraulic cylinder pulling the line to failure. The appropriateness of testing short lengths (i.e., approximately 20 feet) to the investigation of snapback of dock lines that are several hundred feet long may be questioned. The work by Feyrer (Reference 2) shows that the energy per unit length of lines 45-feet long and 90-feet long is approximately the same. It is possible, however, that the failure mechanism or released energy of very long lines may be different because the total stored energy in the line is greater than in shorter lines. The "length effect," as it could be called, is one aspect that cannot be easily addressed in a detailed laboratory test like this one.

The strain rate is another test variable that is difficult to assign a value to with confidence that it really represents field conditions. It is a function of the speed of the ship during the mooring operation and the length of the line. Statistical treatment of available data does indicate that there is no difference in the tensile strength or stored energy of lines loaded at the two extremes of the testing machine used in this investigation. It was decided to use the faster speed for ease of experimentation.

4.2 Test Setup

The test setup is shown in Figure 4-1. The line sample (with eye splices in both ends) passes around a 1-inch diameter pin (called the failure pin) with one end attached to the test machine crosshead and the other end attached to a pin in the snapback fixture (called the clevis pin). A grid of 6-inch squares behind the line provides a spatial reference for velocity measurements. A velocity measurement camera (located above and to one side of the test machine), trained on the line sample with the grid behind it, records the first 8 feet of movement of the end of the line after it fails and pulls away from the pin. That displacement data is used to calculate the velocity of the line as described in Section 5.0. Each line sample is 20 feet long, 3 feet of that length is between the clevis pin and the failure pin. The eye splice on each end is 9 inches long when the legs of the splice are held together.

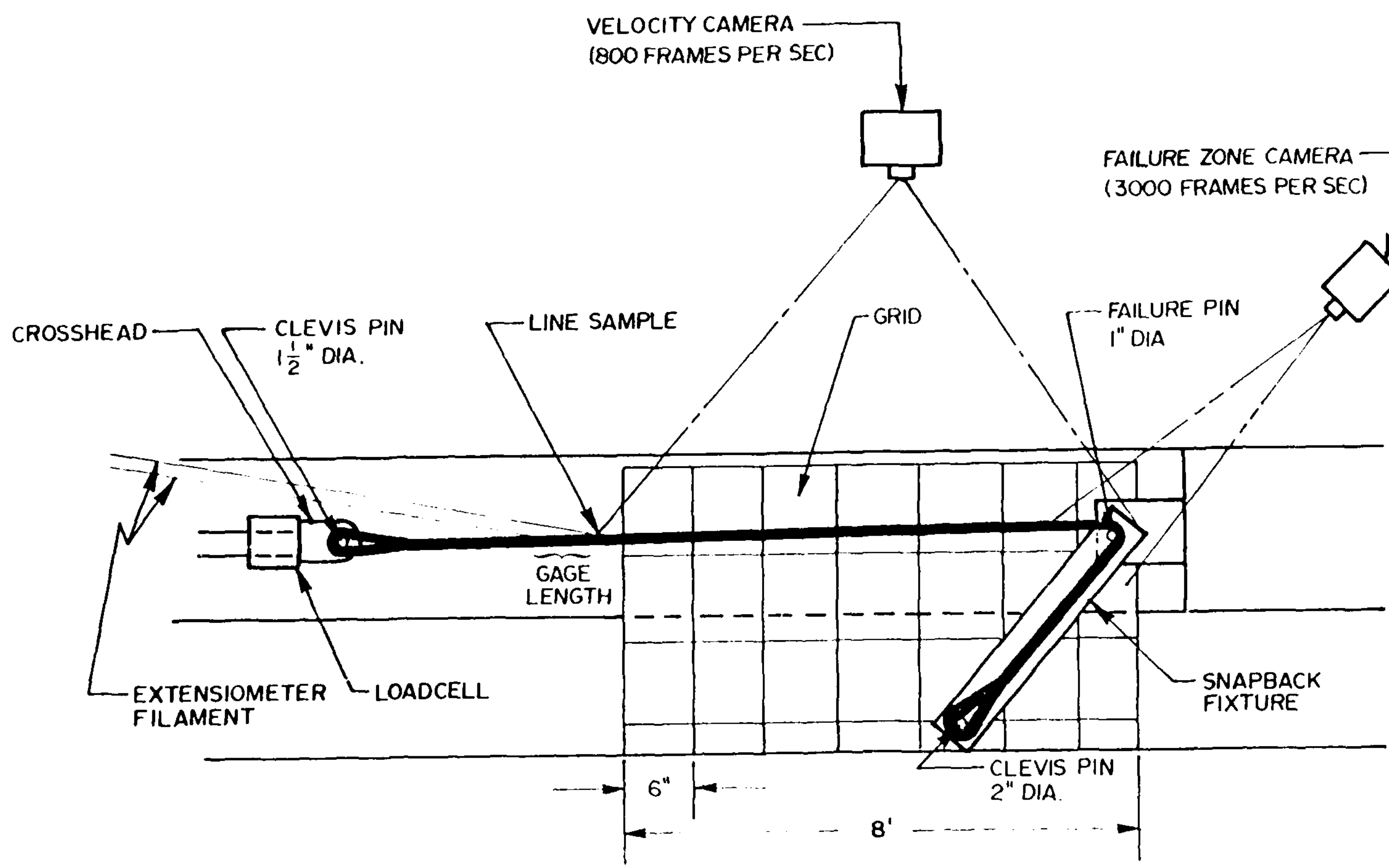


FIGURE 4-1

TEST SETUP

The failure zone camera, positioned in line with and above the line sample, records events on the failure pin.

The velocity measurement camera viewing field is limited to 8 feet because of the ceiling height and configuration of the test machine frame. Analysis of detailed data from Feyrer (Reference 2) indicates that 65% of the kinetic energy of a line sample is contained within the 30% of the total line length that is adjacent to the fracture point. Since the kinetic energy calculation in this experiment is used only to quantify the energy release of each sample for comparison with other samples, there is no need to observe the entire length of travel of the sample as it would be if, for example, an effort was made to calculate the total kinetic energy released by the entire line.

The crosshead speed during the test was approximately 33 inches per minute. The speed was originally selected because it is the maximum speed of the test machine and it was felt that a relatively rapid application of load is probably more realistic than a very slow one. However, analysis of stored energy data available from Reference 3 for nylon, polyester and polypropylene lines indicate that for an order of magnitude change in crosshead speed, there is no statistical difference in the stored energy.

The velocity measurement camera, operating at 800 frames per second, allows approximately 6-10 frames of data for each test. The failure zone camera, operating at 3000 frames per second, allows in some cases only 2-3 frames of data. Details of the cameras are discussed in Appendix A.

A load cell mounted on the testing machine crosshead measures the tension in the line and records it on an x-y plotter. Elongation in the line sample is measured with an extensiometer located at some distance from the line; the elongation is transmitted to the extensiometer by fine filaments that are connected to the line sample approximately 6 inches apart (called the gauge length). Elongation is recorded on the x-y plotter along with the load so that the load-elongation curve is produced graphically during each test. The load-elongation curve is used to calculate the stored energy as described in Section 5.0.

All experimentation was performed in the Cyclic/Tensile Testing Machine at the U.S. Coast Guard R&D Center.

4.3 Line Samples

The lines selected for investigation (Table 4-1) represent a broad range of material and construction combinations that are currently in use in the U.S. and are available commercially or through the Federal Supply System. Two lines not normally used in the U.S. are included because of the potential reduction in snapback. Samples of the basic constructions are shown in Figure 4-2. They are:

a. Double Braid - Basic construction is a braided core inside a braided cover. This construction is investigated because it is widely used in the Coast Guard and Navy.

b. 8-Strand Plait - Basic construction is four pairs of strand sets.

c. Cross-Lay - Cross-lay line was selected because it is constructed like wire rope which fails in a cascading manner and may reduce snapback (Reference 2). Cross-lay line has six strands laid around a central core (Figure 4-3). Each strand has eight nylon monofilaments (.065 inches diameter) laid helically around the strand core of loosely twisted multifilaments. Between each monofilament is a smaller filler strand of twisted multifilaments that maintain the spacing between the monofilaments. The central core of the line consists of 22 strands of loosely twisted multifilaments. Nylon cross-lay line is made by Vermeire NV of Belgium under the name of Atlas Synthetic Wire Rope.

d. 3-Strand Twisted - monofilament and staple fiber yarn.

Staple fiber yarns are made up of discontinuous multifilaments rather than continuous monofilaments. To make multifilaments, polypropylene pellets are melted and extruded into multifilaments which are wound onto a drum. When the drum is full, a knife drawn across the drum cuts the multifilaments and produces a hank of polypropylene multifilaments approximately 54 inches long. Processing of staple fiber is very much like manila in that hanks are combed and twisted into yarns and finished in the 3-strand construction. Staple fiber has a hairy appearance and feels much like manila line. The large number of discontinuous filaments in staple fiber construction is thought to promote realignment of the fibers so that the load is carried more uniformly by all strands. Staple fiber line is much more flexible than the monofilament line that is available in the Federal Supply System. The size difference in the basic yarns of the two constructions is shown in Figure 4-4. The very fine multifilament is the basic element of the staple fiber construction and the rolled tape yarn is the basic element of the conventional construction from the Federal Supply System.

Polypropylene 3-strand staple fiber line is extensively used by the Danish Navy because of the reduced snapback risk and low cost.

TABLE 4-1

LINE SAMPLE SPECIFICATIONS

MATL/CONSTRUCTION	DIA (in)	SUPPLIER	RATED BREAK STRENGTH (lb)
Nylon Double Braid	7/8	MIL-R-24050	22,500
8-Strand Plaited	7/8	MIL-R-24337	19,000
3-Strand Twisted	7/8	MIL-R-17343	19,000
Cross-Lay (Atlas)	7/8 (22mm)	VERMEIRE N.V. (BELGIUM)	26,700
Polyester Double Braid	7/8	Samson-Ocean Systems	27,000
8-Strand Plaited	3/4	Columbian Rope Company	12,500
3-Strand Twisted	1	MIL-R-30500	18,500
Polypropylene 8-Strand Plaited	3/4	Columbian Rope Company	8,500
3-Strand Twisted (Monofilament)	1	MIL-R-24049	13,000
3-Strand Twisted (Staplefiber)	7/8 (22mm)	British Ropes	13,000

a – Double Braid

b – 8 – Strand Plait

c – Cross – Lay

d – 3 – Strand Twisted (Monofil.)

3 – Strand Twisted (Staplefiber)

FIGURE 4-2 LINE SAMPLES

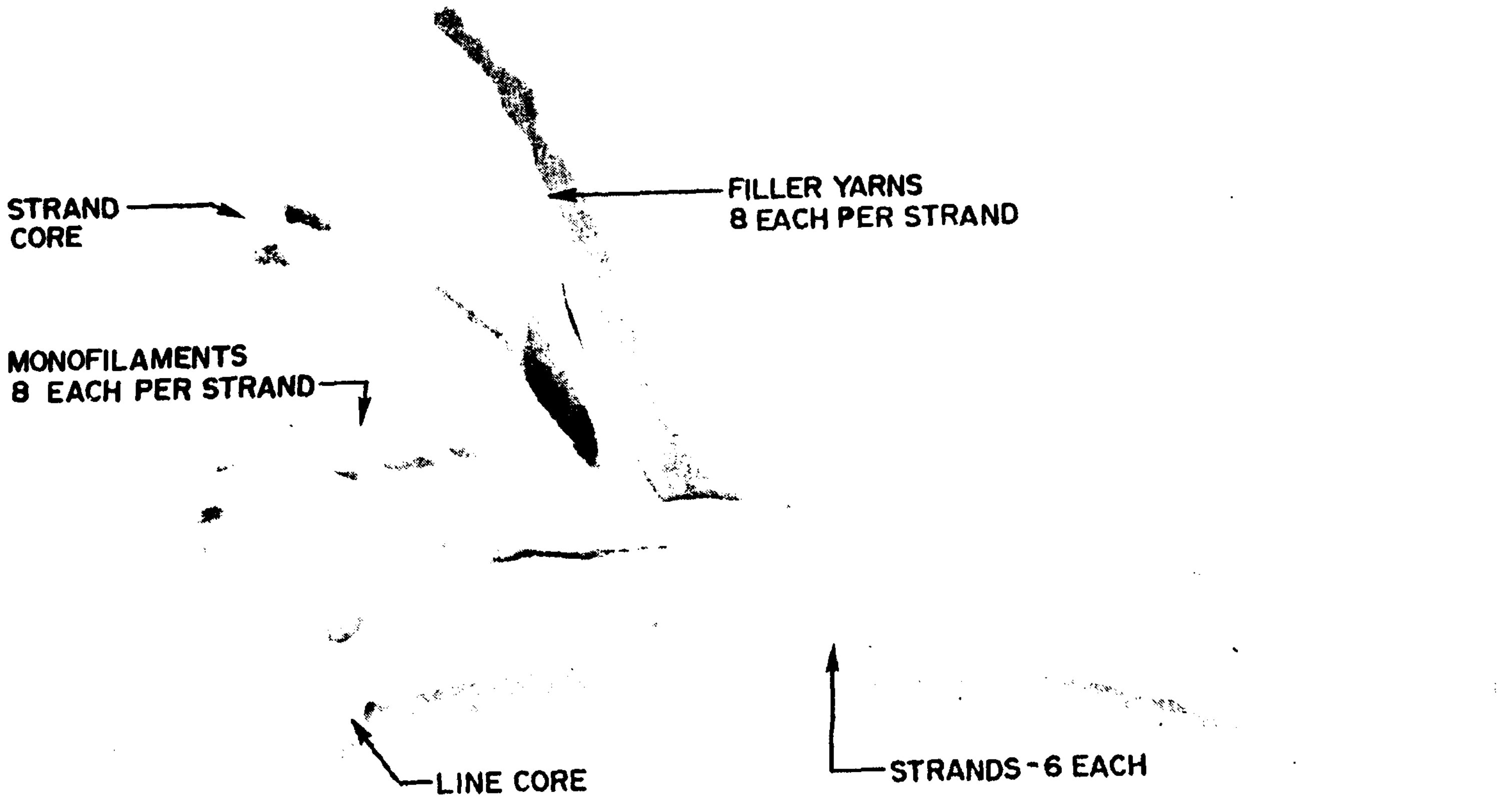
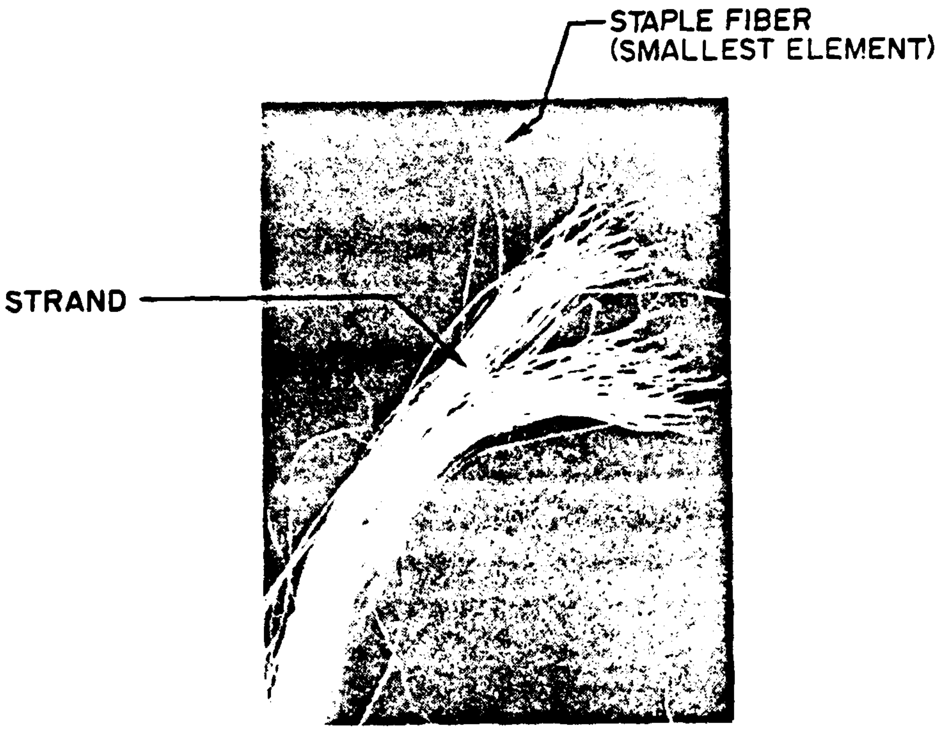
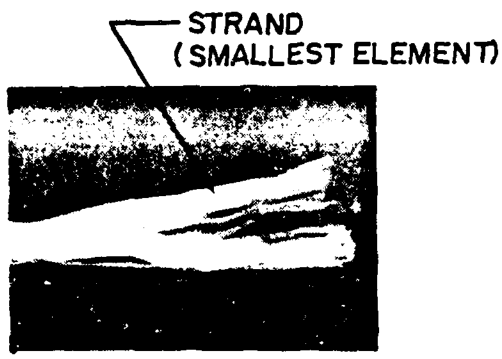


FIGURE 4-3

CROSS-LAY CONSTRUCTION



STAPLE FIBER



MONOFILAMENT

FIGURE 4-4 MONOFILAMENT AND STAPLE FIBER FILAMENTS

4.4 Test Procedure

The experimental portion of this investigation consists of three phases:

a. Baseline Tensile Testing - Samples 8-feet long (see Table 4-2) with eyesplices in each end are conditioned by loading to 20 percent of the manufacturer's rated break strength (RBS) ten times to set the construction and splices. Then the samples are loaded to failure in a straight pull between eyes to record the load-elongation curve and the maximum tensile strength. Three samples of each type line are tested and the results averaged.

b. Fixture Calibration Tests - This test determines the load at which each sample type fails over the pin in the snapback fixture so that the cameras can be started. Each sample, 20 feet long, is conditioned by loading to 20 percent of the baseline break strength (determined above) ten times in a straight pull between eyes. Then the sample is placed around the snapback fixture as described in Section 4.2 and loaded until failure occurs at the failure pin. The load-elongation curve is recorded to determine the maximum tensile load (i.e., the highest point on the load-elongation curve) to be used to start the high-speed movie cameras as described in the next section. Three samples of each type line are tested.

c. Velocity Measurement and Failure Zone Observation Tests - Each sample, 20 feet long, is conditioned by loading to 20 percent of the baseline tensile strength ten times as described above and placed around the snapback fixture. As load is applied to the test sample, the high-speed cameras are started just below the load determined in the fixture calibration tests. The velocity camera, operating at 800 frames per second, permits approximately six seconds of recording time with two seconds required to bring the camera up to operating speed. The failure zone camera, operating at 3000 frames per second, permits approximately three seconds of recording time. The load-elongation curve is recorded during the tests for use in calculating the stored energy.

TABLE 4-2

TEST SAMPLE DIMENSIONS

	Eye Length	Total Sample Length	Pin Diameter / Line Diameter	Eye Length / Pin Diameter
Baseline Tensile Test	9"	8'	2.0	5.1
Fixture Calibration and Snapback Test	9"	20'		

5.0 DATA REDUCTION AND ANALYSIS SCHEME

The primary objective of this investigation is the quantification and characterization of the snapback behavior of synthetic lines. To accomplish this, a rationale is developed for coefficients that describe fundamental snapback properties of a synthetic line material/construction combination without regard to diameter. These coefficients allow a comparison of properties but with no tie to absolute engineering units. A second rationale is developed to adjust data from individual line material/construction combinations so that they can be compared on an absolute basis. This method adjusts the properties of lines so that it appears that several similar lines are all tested in exactly the same manner so that the results can be compared directly. The synthetic lines investigated are compared quantitatively in three ways:

a. Storage Energy, - The energy that is stored in the line before failure.

b. Snapback Energy - The energy released after a line fails.

c. Energy Release Ratio - A ratio of a and b above and indicates that portion of the storage energy that is released when the line fails.

The following paragraphs describe the quantitative data that is collected for this type of analysis, how it is collected and reduced, and the normalization technique that is applied to the data so that the behavior of the various lines can be compared. No failure zone data is discussed in this section because that data is observational, qualitative information. That data is described in detail in subsequent sections.

5.1 Storage Energy

Storage energy, E_i, is the energy that a line stores during loading. It is the energy that acts as a shock absorber to mitigate surge loads during a mooring operation. The potential for storage energy is the type of property that is desirable in a mooring or docking line. Storage energy will be compared with the amount of energy released at failure to show how efficient a line is at dissipating energy and thereby reducing the danger from snapback.

The energy, U, stored per unit length, l, in a line as it is loaded is given by

$$\frac{U}{l} = \int T \, d\epsilon \qquad \text{(V-1)}$$

where
T = is the tension
ϵ = is the strain

It is represented by the area under the load-elongation curve. The load-elongation curve can be expressed as a third-order polynomial regression equation of the form

$$\epsilon = A + BT + CT^2 + DT^3 \tag{V-2}$$

where A, B, C and D are constants.

The derivative of a strain, ϵ, with respect to the tension, T, is

$$\frac{d\epsilon}{dT} = B + 2CT + 3DT^2 \tag{V-3}$$

Substituting equation (V-3) into equation (V-1),

$$\frac{U}{\ell} = \int (BT + 2CT^2 + 3DT^3)\,dT$$

Integrating between zero and the tension in the line at failure,

$$E_i = \frac{U}{\ell} = \frac{BT^2}{2} + \frac{2CT^3}{3} + \frac{3}{4}DT^4 \Big|_0^T \tag{V-4}$$

where E_i is the energy stored in the line at failure.

5.2 Snapback Energy

Snapback energy is that portion of the stored energy that is converted to kinetic energy when the line fails. It is the property of the mooring line, or docking line, that is best minimized because of the potential for serious injury to dock personnel who may be struck by the line as it recoils.

Kinetic energy is used as a measure of snapback in this investigation. The kinetic energy is calculated with the average velocity of the fractured end of the line obtained from the high-speed films. The kinetic energy of the end of the line is intended only as an index of the snapback potential and is not intended to infer the kinetic energy of the total length of the line. Calculating the kinetic energy from the entire line is beyond the capability of this experimental setup. Since the velocity is not constant for all segments of the line, a velocity profile is required for the entire length if the total kinetic energy is to be calculated. This is not possible, however, because the majority of the line is out of the field of view of the camera (as discussed in Section 4.2). The kinetic energy calculated from the end velocity may not be directly compared with data from the other studies that use the velocity of all segments of the line.

The kinetic energy, called the snapback energy, E_s, is calculated from the equation

$$E_s = \frac{1}{2}\frac{m}{g}V^2 \tag{V-5}$$

where m = Unit weight of the line
V = Velocity of the fractured end of the line; averaged over 6-10 frames of data

5.3 Energy Release Ratio

The Energy Release Ratio is the ratio of the snapback energy to the storage energy.

$$R = \frac{E_s}{E_i} \qquad \text{(V-6)}$$

This ratio indicates what percentage of the energy that goes into the line during loading is released at failure; it is a dimensionless indicator. It is quite possible that two lines with the same energy release ratio could actually release energies that are quite different in absolute units. A low Energy Release Ratio indicates some inherent capability of the line to dissipate a relatively large amount of energy either through material damping or a phased release of energy during failure. In selecting a mooring or docking line, a line with a Low Energy Release ratio is desirable.

5.4 Storage Energy Potential

Storage Energy Potential is the fundamental characteristic of a line of a particular material/construction combination (of any diameter) to absorb or store energy. Comparing the storage energy potential of various lines will indicate which line type has the inherent capability to absorb energy. A technique to calculate the storage energy of various lines of different diameters for comparison of absolute storage energy will be discussed in a later section.

It is assumed that the storage energy, E_i, of a line is expressed by (Reference 4, page 2-9)

$$E_i = TC\epsilon \qquad \text{(V-7)}$$

where C = Shape factor of the load-elongation curve of the line
T = Break strength of line
ϵ = Strain at failure

It is assumed, for comparison purposes only, that the strain at failure, ϵ, and the shape of the load-elongation curve, C, of a line type is fundamentally the same regardless of diameter. Therefore storage energy is a function of the tension in the line. Equation (V-7) can be rewritten

$$E_i = (C\epsilon)T$$

or

$$E_i = E_i^{I}T$$

and this can be rewritten in the form

$$E_i^{I} = \frac{E_i}{T} \qquad \text{(V-7A)}$$

The Storage Energy Potential, E_i', is a fundamental quantity that indicates the capacity of a line to absorb energy. It can be thought of as the slope of energy-tension curve; a large E_i' means that a line absorbs more energy as tension is applied than does a line with a lower E_i'. In comparing types of mooring or docking lines, a large E_i' value is preferable because that type of line can absorb more energy at the same tension level than other lines. There are data presented in References 3, 5 and 6 that indicate, as an initial assumption, equation (V-7A) is fundamental to a type of line (i.e., material/construction) and is independent of diameter.

5.5 Snapback Energy Potential

Snapback Energy Potential, E_s', is a quantity that represents the fundamental capacity of a line to release energy at failure. It represents the fundamental snapback capacity of the line just as the Storage Energy Potential represents the storage energy capacity. It is given by

$$E_s' = \frac{E_s}{T} \qquad \text{(V-8)}$$

where E_s = Energy released as line fails
T = Tension at failure

There is a theoretical basis and some experimental data to justify using equation (V-8) as a general indicator of snapback potential. In the simplest case, it is assumed that all energy is converted to snapback energy upon failure (Paul, Reference 4). Therefore

$$E_s = E_i$$

and using equation (V-7) the above becomes

$$E_s = TC\epsilon \qquad \text{(V-8A)}$$

Since $C\epsilon$ is assumed to be constant for a line (for purposes of comparison as described in Section 5.4), it appears that the snapback energy and the tension at failure exhibit a linear relationship and are primarily independent of diameter. There is not sufficient data yet to completely verify the independence from diameter, however, data from Wesler and Parker (Reference 1) indicates that snapback energy and tension are quite linear. This is true especially at reasonably high tensions where most cases of accidental failure occur. Further supporting data can be drawn from work by Stevens (Reference 6) on synthetic yarns and fibers.

5.6 Absolute Snapback and Storage Energies

The energy potentials discussed in Sections 5.4 and 5.5 are indicators of the capacity of a line to store or release energy. These energy potentials are used to compare one type of line with another. An alternate method of comparing the snapback and storage energies of lines is discussed in this section. To compare lines directly, the conditions of test must be the same. Since this is rarely achieved in the laboratory, a method must be developed to treat data so that it appears that the lines were all tested identically. Two bases of adjustment (i.e., extrapolation) are possible: (a) all lines are subject to equal tension at failure, or (b) all lines are subject to equal storage energy at failure. The case for either approach is sound; the equal tension method is described here because it is probably easier to relate this method to strength requirements of a design application.

The Equal Tension Basis technique adjusts (i.e., extrapolates) the storage and snapback energy data of the various lines so that it appears that the lines tested have the same tensile strength and fail at the same percentage of tensile strength. The adjustment technique can be broken down into two steps to facilitate explanation. Both steps are based on the fact that small changes in tension produce small linear changes in storage and snapback energy as discussed in Section 5.4.

The adjusted energy is given by

$$(E_a) = E \times \frac{T_T}{BS} \times \frac{\% T_T}{\% BS} \qquad \text{(V-9)}$$

where $E_{(a)}$ = is either storage or snapback energy, adjusted
E = is either the storage or snapback energy of the line with a break strength, BS, that fails at some percentage of its strength (i.e., % BS)
T_T = Adjusted maximum strength of the line
BS = Actual measured break strength of the line
$\%T_T$ = Percentage of the adjusted maximum strength at which snapback is to be evaluated for all line types
% BS = Percentage of the break strength at which test sample actually fails and at which the storage energy and snapback energy are experimentally measured

The second factor to the right of the equal sign effectively adjusts the energy to what it would be if the line that was tested had a maximum strength of T_T rather than BS. The third factor adjusts the energy so that all lines appear to fail at the same percentage of their maximum strength. It is preferable to have all lines tested in approximately the same region of the load-elongation curve to minimize any error caused by the non-linearity of load-elongation curves. In summary, T_T is the load level to which the energy is being extrapolated based on an energy measurment at load level, BS.

5.7 Snapback Velocity Extrapolation

Snapback velocity is a function of tension in the line when it fails. The following method allows the adjustment of the velocity from one tension to another so that they can be compared.

Theoretically the energy stored in a line before failure (equation (V-7)) is equal to the energy released after failure (equation (V-5)). That is,

$$\frac{1}{2}\frac{m}{g}V^2 = TC\epsilon$$

This suggests that the tension in a line is a linear relationship of the square of the velocity and that a proportionality can be established. Therefore

$$\frac{V_2^2}{V_1^2} = \frac{T_2}{T_1}$$

or

$$V_2 = V_1\sqrt{\frac{T_2}{T_1}} \qquad \text{(V-10)}$$

where V_1 = is the snapback velocity measured when failure occurs at tension, T_1

V_2 = is the snapback velocity expected if failure occurs at tension, T_2

6.0 TEST DATA

Velocity data for 3-strand line is not discussed in detail because that construction does not consistently fail completely when pulled around the failure pin as described in Section 4.4. Generally two strands fail leaving one strand to hold the line together. An additional set of tests, described in Appendix B, were conducted to determine if that failure mode is representative of 3-strand line or is just caused by this particular test method (i.e., bending around a small diameter pin.) Three-strand line as well as polypropylene 8-strand plaited and nylon cross-lay line were tensile tested by wrapping one end four times around a 10-1/2 inch bollard and pulling on the other end with an eyesplice in it. In all cases except nylon 3-strand line, the lines failed the same way that they failed when pulled around the snapback fixture. Nylon 3-strand line, however, failed completely when pulled around the 10-1/2 inch diameter bollard but fails partially in the snapback fixture. Since the snapback fixture sample fails at only 60 percent of the tension of the eye/bollard samples, there is correspondingly less energy in the line at failure. When one or two strands fail, they may not have enough energy in them to cause the remaining strand to fail when that energy is transferred to it. The same situation is discussed in the section on "Length Effect" in Section 4.1.

6.1 Baseline Tensile Tests

All line samples meet the Milspec or manufacturer's rated breaking strength except for nylon cross-lay, polyester double-braid, and polypropylene 3-strand twisted monofilament lines (Table 6-1). No other data is available from this investigation that might explain the discrepancy between the values for polyester double-braid line. The results of separate tests described in Appendix B do show that nylon cross-lay line is capable of the load stated by the manufacturer. The discrepancy between the baseline tensile strength and the eye/bollard test data has not been explained. Data for the polypropylene 3-strand monofilament line from the eye/bollard test (Appendix B) indicate that higher strengths are obtained in the eye/bollard test conditions; however, there is no statistical significance between the baseline tensile strength and the eye/bollard strength values. Both are somewhat lower than the rated break strength described by the Milspec.

6.2 Storage Energy

The storage energy is given by equation (V-4). The coefficients for that equation are found in Table 6-2 and the resulting Storage Energies appear in Table 6-1. The coefficients in Table 6-2 are for the third-order polynomial regression equation of the load-elongation curve (equation (V-2)) used to derive equation (V-4). These storage energies cannot be compared directly because they do not represent the same test conditions. The method for adjusting this type of data is discussed in Section 5.6 and applied to data in Section 7.8.

TABLE 6-1 TEST RESULTS

MATERIAL/ CONSTRUCTION	DIA (in)	RATED BREAK STRENGTH (lbs)	BASELINE STRENGTH (lbs)	BEND-OVER PIN STRENGTH (lbs.)	STORAGE ENERGY (ft-lb/ft)	AVERAGE SNAPBACK VELOCITY (ft/sec)	SNAPBACK ENERGY (ft-lb/ft)
Nylon Double Braid	7/8	22500	23712 (1985)	15064 (1794)	1257	505 (24.2)	894
8-Strand Plaited	7/8	19000	19634 (1985)	12170 (1325)	1388	529 (7.0)	808
3-Strand Twisted	7/8	19000	19932 (1201)	13217 (754)	1278	---	---
Cross Lay	7/8	26700 nom. 24300 min.	21101 (2566)	14600 (1244)	1119	374 (61.0)	556
Polyester Double Braid (with Duron)	7/8	27000	21945 (2558)	15000 (961)	1466	359 (25.5)	506
8-Strand Plaited	3/4	12500	13284 (2792)	7886 (1932)	441	358 (23.3)	370
3-Strand Twisted	1	18500	18320 (394)	9760 (1976)	951	---	---
Polypropylene 8-Strand Plaited	3/4	8500	8568 (762)	4869	343	418 (39.6)	287
3-Strand Twisted (Monofilament)	3/4	13000	19939 (310)	5640 (760)	324	143(1)	---
3-Strand Twisted (Staple Fiber)	7/8	13000	13077 (1275)	6346 (937)	447	337(2)	269

Standard Deviations shown in parenthesis (1) Partial Failure (One Strand) (2) Complete Failure; one sample

TABLE 6-2

STORAGE ENERGY EQUATION COEFFICIENTS

	A $X10^{-2}$	B $X10^{-4}$	C $X10^{-8}$	D $X10^{-12}$	Average Max. Tension
Nylon Double-Braid	.4591	.7212	-.627	.1907	15064
8-Strand Plait	.344	.887	-.862	.334	12170
3-Strand					13217
Cross-lay	.8716	.4612	-.3469	.9983	14600
Polyester Double-Braid	-.6354	.2496	-.0193	-.0239	15000
8-Strand Plait	.8346	.657	-.753	.358	7886
3-Strand Twisted	.5941	.7997	-.732	.247	9760
Polypropylene					
8-Strand Plait	.2233	.5849	.0612	-.689	4800
3-Strand Twisted (Monofilament)	.7977	.289	-.156	.06511	5640
3-Strand Staple Fiber)	.765	.492	-.259	-.085	6346

6.3 Snapback Velocities

The snapback velocity used to represent each line sample appears in Table 6-1. This data is used to calculate the kinetic energy of the line in the next section. As discussed in Section 5.2, this is the average velocity in the fractured end of the line. Comparing snapback velocity as produced by different experimenters can be difficult because of the difference in the method used to calculate the velocity. The velocity decreases from the point of failure along the line which means that the calculated velocity will depend on how much of the line is included in the average. An example of this is shown in the velocity data for markers spaced one foot apart in Figure 6-1; "end" is the fractured end and Marker 1 is located one foot (in the unstretched condition) from the fractured end in the direction of the fixed end. If the velocity of all markers is used to calculate the representative velocity of the line, the average velocity is 297 feet per second; that is compared to an average velocity of 400 feet per second just for the fractured end. That 35% difference in velocity actually represents a 42% difference in kinetic energy. This variation is observed in Section 7.2 where the kinetic energies for this investigation and those of Feyrer (Reference 2) are compared.

6.4 Snapback Energy

The snapback energy for each line sample is calculated using equation (V-5) with the velocities in Table 6-1 and the linear densities in Table 6-3. The resulting snapback energies appear in Table 6-1.

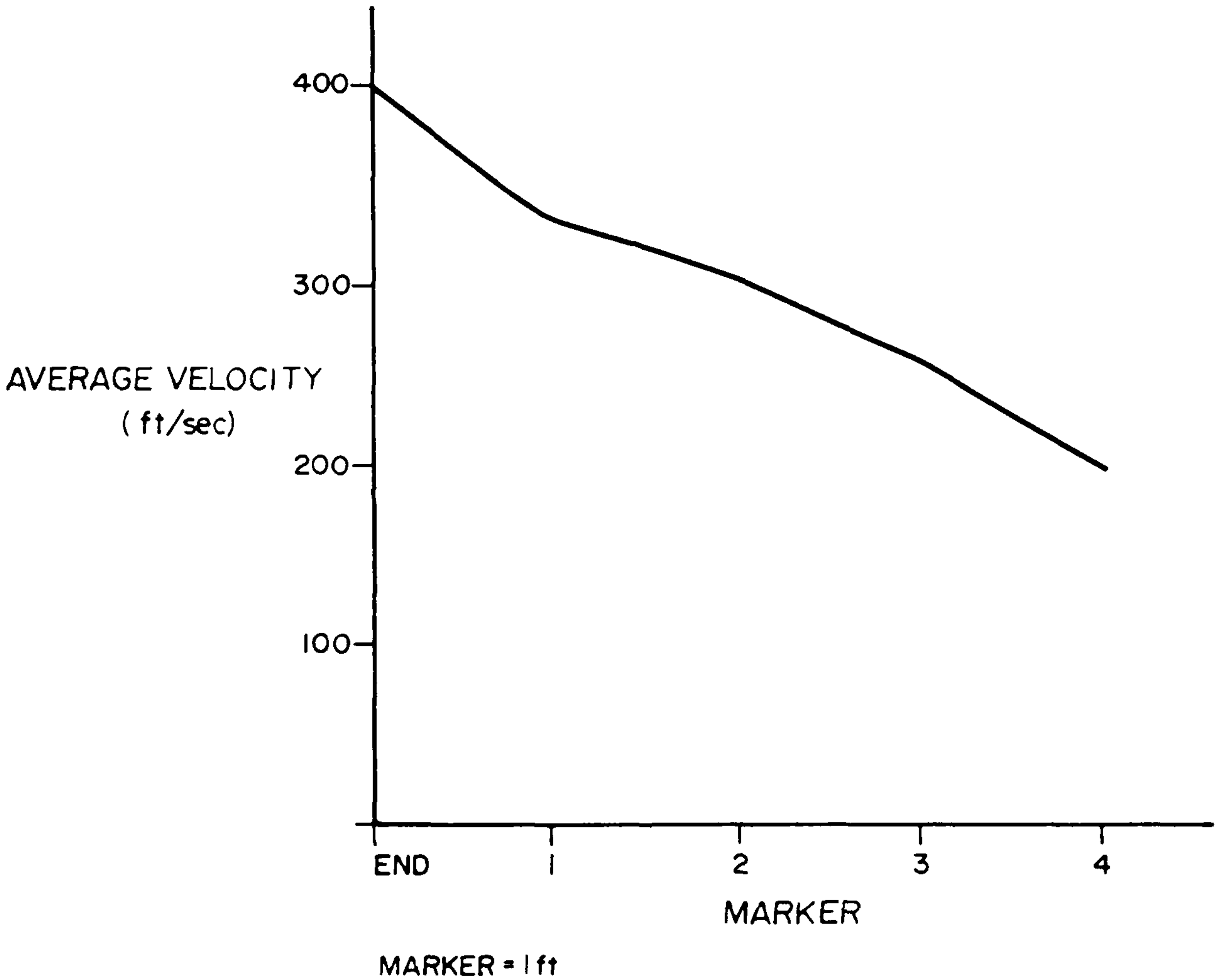


FIGURE 6-1 END VELOCITY PROFILE OF CROSS-LAY LINES

TABLE 6-3

LINE LINEAR DENSITIES

MATERIAL/CONSTRUCTION	DIA (in)	WEIGHT PER UNIT LENGTH (lb/ft) (1)
Nylon Double Braid	7/8	.226
8-Strand Plaited	7/8	.200
3-Strand Twisted	7/8	.193
Cross-Lay	7/8	.253
Polyester Double-Braid	7/8	.253
8-Strand Plaited	3/4	.186
3-Strand Twisted	1	.326
Polypropylene		
8-Strand Plaited	3/4	.106
3-Strand Twisted (Monofilament)	1	.146
3-Strand Twisted (Staple Fiber)	7/8	.153

(1) Measured Experimentally

7.0 RESULTS

The objective of this investigation includes development of a technique to quantify the snapback phenomena as well as the quantification of the snapback characteristics of the specific lines tested. For this reason several of the sections below are sub-divided into two parts to reflect the dual analysis objectives of the data. In these sub-divisions, (a) the method of analyzing the data is evaluated, and (b) the results of the analysis method with regard to the specific lines are discussed.

7.1 Storage Energy Potential

The Storage Energy Potentials (Table 7-1) of the lines tested are calculated by using equations (V-7A) and the storage energy and bend-over-pin strengths from Table 6-1.

Evaluation of the Analysis Method

The Storage Energy Potential can theoretically be calculated using the stored energy at the maximum break strength, as recorded during the baseline tensile test, or the bend-over-pin strength from the snapback fixture. It might be expected that the Storage Energy Potential calculated from these two tests would yield the same results. In these tests, the results are not consistently the same and occasionally they are significantly different. The difference is due primarily to the fact that the load-elongation curves (and therefore the area under them representing the Storage Energy) for the two loading conditions are different for some of the lines tested; the difference has not been explained but it is probably due to the difference in strain rates between the two tests. This is not consistent with preliminary calculations (discussed in section 4.1) that indicate that strain rate should not have a significant effect on storage energy. Since the Snapback Energy is compared to the Storage Energy which is calculated from the snapback fixture data, it is felt that the overall results are more accurate if both energies are calculated from the same loading conditions.

The Storage Energy Potential of some lines from other sources are shown in Table 7-1, also. While there is insufficient data for statistical analysis, the data in general appears to support the supposition (set forth in Section 5.4) that the Storage Energy is fundamental to a line material/construction combination and is independent of diameter.

7.2 Snapback Energy Potential

Snapback Energy Potential is calculated using equation (V-8) using the Snapback Energy and Bend-over-pin strengths found in Table 6-1; the results appear in Table 7-2.

Evaluation of Analysis Method

The Snapback Energy Potential is a function of the average velocity of the line. As discussed in Section 5.2, the average velocity of the line is affected by the number of line segments used to calculate the average because the segment velocity tends to decrease with distance from the failure point.

TABLE 7-1

STORAGE ENERGY POTENTIALS

$$\left[\frac{ft - lb}{\frac{ft}{lb_f}}\right]$$

		Dia (in.)	E'_i	Dia (in.)	E'_i
Nylon	Double braid	7/8	.084	2 1/2	.078 (1) .080 (2)
	8-Strand Plait	7/8	.114	2 1/4 1/2	.100 (1) .094 (2)
	Cross-Lay	7/8	.076	---	---
Polyester	Double Braid	7/8	.097	---	---
	8-Strand Plait.	3/4	.056	2 1/2" 1/2	.065 (1) .069 (2)
Polypropylene	8-Strand Plait.	3/4	.092	3"	.075 (1)
	3-Strand Staple Fiber	7/8	.070	---	---

(1) from Feyrer (1978)

(2) from Bitting, 1975 (Report No. CG-D-104-76)

Table 7-2

SNAPBACK ENERGY POTENTIALS

$$\left[\frac{\frac{ft\text{-}lb}{ft}}{lb_f}\right]$$

	Double Braid	8-Strand Plaited	3-Strand	Cross-Lay
Nylon	.059 (.0057)	.066 (.0017)	---	.035 (.0108)
Polyester	.033 (.0048)	.046 (.0061)	---	---
Polypropylene	---	.059	.042 (Staple Fiber)	---

Standard Deviation shown in parenthesis

COMPARISON WITH OTHER DATA

		From Above	Feyrer (1)
Nylon	Double-Braid	.059	.04
	8-Strand Plait.	.066	.037
Polyester 8-Strand Plait.		.046	.05

(1) from Feyrer (1978)

Unless the same method is used to calculate the average velocity (i.e. average kinetic energy), the Snapback Energy Potentials are difficult to compare directly. The Snapback Energy Potentials from Feyrer (shown in Table 7-2) are nominally 30%-50% less than those observed in this investigation because he averaged the kinetic energy for the entire length of the line (rather than the end velocity as in this investigation). This corresponds to the reduction in velocity caused by averaging as discussed in Section 6.3. In summary, in calculating the Snapback Energy Potential, the method for calculating the average velocity must be consistent and well-stated in supporting test reports.

Comparison of the Lines Tested

Analyzing the results in Table 7-2 yields insights into the Energy Release Potential of the lines tested. All results discussed below are based on statistical tests with a 90% confidence limit.

Nylon line has a significantly higher Snapback Energy Potential than polyester line (in double braid and 8-strand plaited construction). If the results from the nylon double braid and 8-strand plaited line tests are grouped together and the polyester double braid and 8-strand plait line tests are grouped together, there is a significant difference between the nylon and polyester groups; that is to say, the nylon group has a Snapback Energy Potential that is 60% higher than the polyester group.

The Snapback Energy Potential of 8-strand plaited line is only slightly higher than double braid line. In general, 8-strand plaited line has only slightly higher Snapback Energy Potential than double braid line. The effect of material is much stronger than the construction effect (when comparing nylon and polyester double braid and 8-strand plaited line); that is to say, the difference between a nylon and polyester line is much greater than the difference between double braid and 8-strand plaited line.

The Snapback Energy Potential of nylon cross-lay and polyester double braid line is significantly lower than the other lines tested. For example, the Snapback Energy Potential of nylon cross-lay and polyester double braid is 50% less than nylon double braid and 8-strand plaited line.

It should be noted that in the result above, polypropylene 8-strand plaited and 3-strand twisted staple fiber line and nylon cross-lay line are not included in comparisons of the Snapback Energy Potential of groups of materials or constructions. These lines do not appear uniformly in all groups tested and including them would bias the results; that is to say, since data for cross-lay line is not available in polyester and polypropylene, nylon cross-lay line must be omitted from the grouping of all nylon lines when that group is compared with, for example, all polyester lines. The effect of cross-lay construction is also not represented in the polyester group. The same is true for the exclusion of the polypropylene lines; to include them in groups with the other material/construction combinations would bias the data because polypropylene line is not represented in all line construction groups.

7.3 Energy Release Ratio

Energy Release Ratio is calculated using equation (V-6) with the Storage Energy Potential (Table 7-1) and the Snapback Energy Potential (Table 7-2); the results appear in Table 7-3.

Evaluation of Analysis Method

The trends in Energy Release Ratio from this investigation are generally confirmed by the data from Feyrer (Reference 2) as shown in Table 7-3. The results from Feyrer are less because the Snapback Energy Potentials used by him in his calculations are smaller than those obtained here because of the lower velocities used in the calculations as explained in Section 7.2.

Comparison of Lines Tested

The Energy Release Ratios in Table 7-3 demonstrate that a portion of the energy that is put into a line during loading is not converted to kinetic energy at failure. From the standpoint of snapback, of course, the less energy released as kinetic energy the better.

Nylon and polyester line of the double braid and 8-strand plaited construction show no systematic trends. Nylon double braid and 8-strand plaited line and polyester double braid and 8-strand plaited line have Energy Release Ratios that are distinctly different. However, there is no systematic trend among these values. That is to say, it cannot be determined what general effect construction or material has on the Energy Release Ratio. This is probably true because opposite trends in material and construction are observed; for example, nylon double braid line has a higher Energy Release Ratio than nylon 8-strand plaited line. However, polyester double braid line has a lower energy release ratio than polyester 8-strand plaited line. Parts of these general trends are confirmed by Feyrer's data (Reference 2) which appear in Table 7-3.

Nylon cross-lay and polyester double braid line exhibit much lower Energy Release Ratios than the other lines. Nylon cross-lay and polyester double braid line effectively have the same Energy Release Ratio. These lines have Energy Release Ratios that are approximately one-half the average of all the other lines tested. It is interesting to note that these two material/construction combinations are quite different yet have the same Energy Release Ratio.

7.4 Some Energy Comparisons of the Lines Tested

The sections above discuss individually the Energy Storage Potential, the Snapback Energy Potential, and the Energy Release Ratio. This section draws these sections together to give an overview of the general trends and highlights specific observations. The energy potentials from the previous sections are combined in Table 7-4 for easy comparison.

The materials/constructions tested have a wide range of Storage Energy Potential; the highest Storage Energy Potential is approximately twice the lowest. The Energy Release Ratios vary by approximately 140 percent. Lines that store large amounts of energy do not necessarily release large amounts of energy. The correlation between material/construction Storage Energy and Snapback Energy is not obvious from these tests.

TABLE 7-3

ENERGY RELEASE RATIOS

	Double Braid	8-Strand Plaited	3-Strand Twisted	Cross-Lay
Nylon	.70 (.0656)	.58 (.015)	------	.44 (.141)
Polyester	.343 (.050)	.83 (.1131)	------	------
Polypropylene	------	.65 (.084)	.60	-------

STANDARD DEVIATIONS ARE SHOWN IN PARENTHESIS

COMPARISON WITH OTHER DATA

		From Above	Feyrer
Nylon	Double Braid	.70	.53
	8-Strand Plait.	.58	.37
Polyester	8-Strand Plait.	.83	.77

Polyester double-braid line and a nylon cross-lay line are examples of lines that release a low percentage of energy but also store a relatively high percentage of energy compared to, for instance, nylon double-braid line which is currently used quite extensively for mooring and towing. The Storage Energy Potential of these two lines are within 10%-15% of nylon double-braid line. The proportion of energy released by these lines is approximately half that of nylon double-braid line.

7.5 Failure Mechanisms

As explained in Section 4.0, the Failure Mechanism of line is examined to determine if there is a connection between the way that the line fails and the amount of kinetic energy that a line has when it parts. A line that fails in stages (i.e., cascading failure mechanism) may dissipate energy before it fails completely so that there is less Stored Energy converted to kinetic energy after failure. The paragraphs below describe the failure mechanism and approximate failure time for each line construction tested.

7.5.1 Mechanisms Description

Double Braid - Failure occurs in less than .5 milliseconds at a single point in the line. There is no extension of the failure zone. That is to say, there is no partial failure of strains or elongation in the area where failure will occur. In these observations there is reason to believe that the core fails at the pin just before the cover fails.

8-Strand Plaited - Failure occurs in two modes: (a) complete failure in less than 1 millisecond, or (b) 6-strands fail abruptly, recoil along the two remaining strands for approximately 18 inches, and the last two strands fail in 1 to 1-1/2 milliseconds.

3-Strand - Two-strands fail first and recoil around the line. As load application continues, individual yarns in the last strand fail over a relatively long time. This is particularly true of staple fiber construction in which individual yarns fail in a random manner and final failure results in very little snapback. Speaking informally with several operators and researchers did not yield a consensus on how 3-strand line fails in use. Whether complete or partial failure occurs may be a function of such factors as line length, application of the line to deck equipment (i.e., bending around a small radius), damage (causing loss of strength) to strands, and loading rate.

TABLE 7-4

SUMMARY OF ENERGY CHARACTERISTICS

Storage Energy Potential	$\left[\frac{ft\text{-}lb}{ft/lb}\right]$	Snapback Energy Potential	$\left[\frac{ft\text{-}lb}{ft/lb}\right]$	Energy Release Ratio	
Nylon 8-Strand Plaited	.114	Nylon 8-Strand Plaited	.066	Polyester 8-Strand Plaited	.83
Polyester Double Braid	.097	Polypro 8-Strand Plaited	.059	Nylon Double Braid	.70
Polypro 8-Strand Plaited	.092	Nylon Double Braid	.059	Polypro 8-Strand Plaited	.65
Nylon Double Braid	.084	Polyester 8-Strand Plait	.046	Polypro 3-Strand (staple)	.60
Nylon Cross-Lay	.076	Polypro 3-Strand (staple)	.042	Nylon 8-Strand Plaited	.58
Polypro 3-Strand (staple)	.070	Nylon Cross-Lay	.035	Nylon Cross-Lay	.44
Polyester 8-Strand Plait	.056	Polyester Double Braid	.033	Polyester Double Braid	.34

Cross-Lay - Failure occurs over 3-5 milliseconds during which time considerable noise is emitted, probably by the large monofilaments as they fail. Failure appears to take place over the 12-24 inch length of the line near the failure pin. It appears that strands begin to fail well in advance of complete failure. As failure of strands progresses, the failure zone elongates. This effect is observed in a representation (Figure 7-1) of the velocity of markers (spaced one foot apart) on the line; "End" is the velocity of the fractured end and Marker 1 is one foot from the failure pin at the beginning of the test. In the first three film frames of data (representing .00375 seconds) Marker 1 has already started to move and attained a substantial velocity before the line has failed completely; that is to say, the end has no velocity in the first three frames even though other parts of the line are moving at substantial velocities. As failure nears completion, strand failure accelerates and it is difficult to determine if the central core is the last load-carrying member and the strands fail sequentially or if the sequence of failure is more or less random and perhaps the central core fails part-way through the failure process and a strand is the last to go. A cascading failure mechanism is apparent in this line.

7.5.2 Correlation of Failure Time and Snapback Properties

Double-braid line fails in less than .5 milliseconds and 8-strand plait line fails in approximately 1 millisecond. As discussed in Sections 7.2 and 7.3, 8-strand plait line has only slightly higher Snapback Potential than double-braid line. The closeness of the failure times tend to reinforce that finding. Cross-lay line, on the other hand, has a failure time that is approximately 5 to 10 times greater than double-braid and 8-strand plait line and an Energy Release Ratio that is significantly lower (approximately half in some cases) than most of the other lines tested. This characteristic may be due in part to the fact that cross-lay line is also the only construction that demonstrates the cascading failure mechanism.

7.6 Snapback Path

As discussed in Section 3.4, an understanding of snapback path could aid in laying out work stations around shipboard deck machinery that may enhance the safety of the deck force. Since future plans for snapback work may include a large-scale investigation of snapback path, there is information from this investigation and other laboratory work performed by the author that could guide plans for further investigations.

It appears that there is virtually no motion perpendicular to the original axis of the line if failure occurs in clear line. The line proceeds toward the fixed end with very little axial deviation and impacts the area around the fixed end with such force that sections of the line may fuse together. If a line fails at a location requiring it to retract around a curved form such as a bollard, very substantial off-axis motion results in the line sweeping a wide area. This occurred in tests performed by the author in which eye splices were rotationally loaded so that one leg of the eye splice failed near the splice. The failed leg retracted around the bollard and followed a path at a substantial distance from the original position of the line.

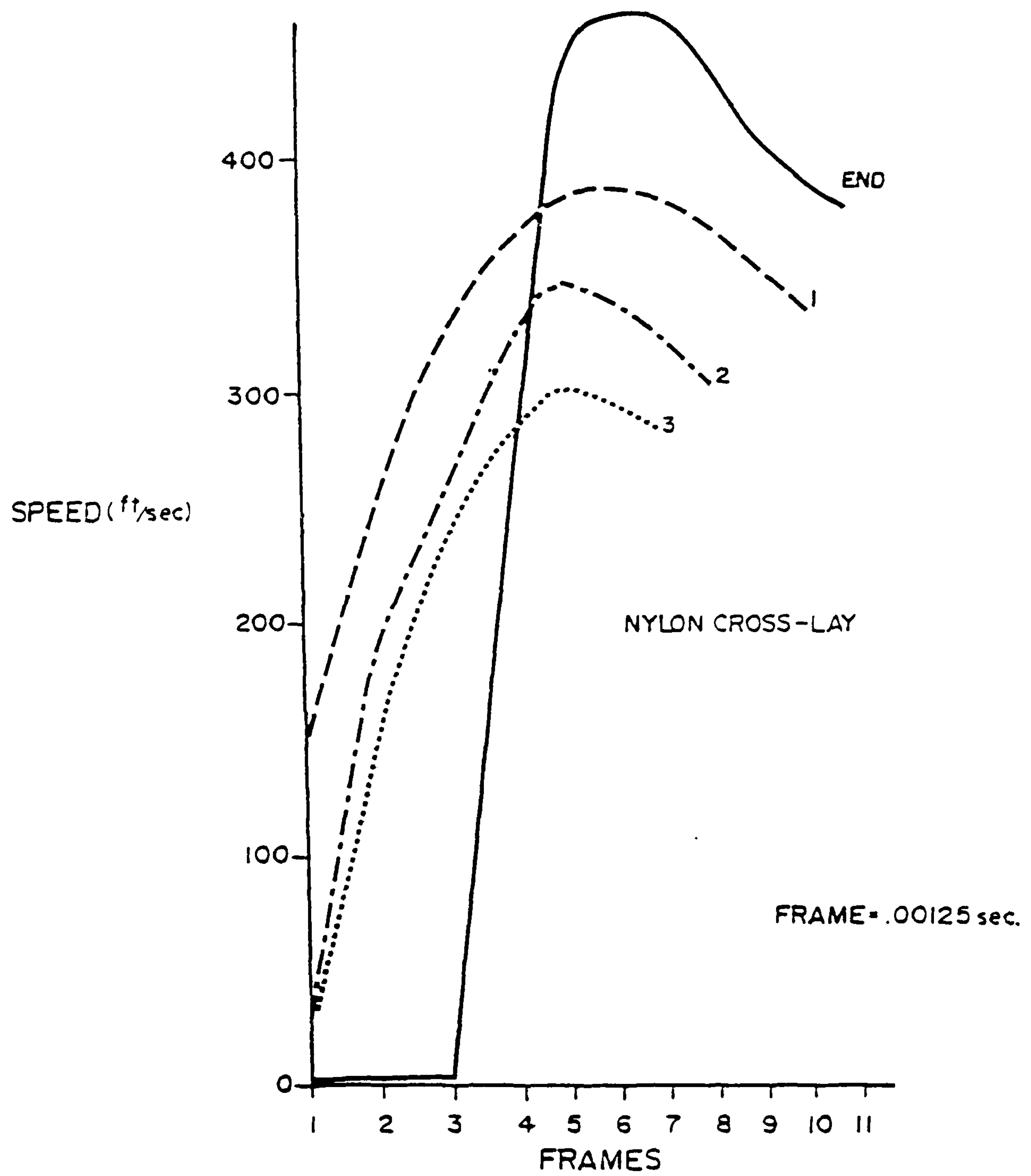


FIGURE 7-1

VELOCITY PROFILE OF MARKERS ON CROSS-LAY LINE

7.7 Interesting Observations About Snapback Velocities

7.7.1 Unique Velocity of Each Line

Available data suggests that snapback velocity for each material/construction combination is a function of only the tension in the line at failure and is independent of diameter; that is to say, each material/construction combination has a characteristic snapback velocity (at a stated percent of break strength). This is indicated by comparing the velocities measured in this investigation (shown in Table 6-1) and similar data reported by Feyrer (Reference 2). To compare velocities, they must be adjusted (i.e. extrapolated) to represent the velocity that would be expected for two lines that fail at the same percent of break strength. Velocities in column 1 in Table 7-5 are adjusted using equation (V-10) (replacing the tension, T, with the % BS) to the % BS in column 3. In other words, the velocities from this study are adjusted so that it appears that they failed at the same percent of break strength as the lines in Feyrer's study. That way they can be compared directly. The "difference" column in Table 7-5 lists the percent difference between the adjusted velocities from this investigation and the velocities of Feyrer's data. For example, the velocity of nylon double-braid line (7/8" dia) is 505 ft/sec. when it fails at 63.5%BS. That velocity extrapolated to 82% BS is 573 ft/sec. The velocity of 2-inch diameter line failing at 82% BS is 604 ft/sec. The difference between the velocity for 7/8" and 2" diameter line is 5%. The close comparison in this and most cases suggests that snapback velocity may be generally a function of tension at failure and not diameter.

7.7.2 Theoretical Snapback Velocities

It has been suggested in the literature (Reference 4, page 2-9) that it is possible to calculate the snapback velocity from the assumption that all stored energy is converted to kinetic energy when the line fails. This is not true as demonstrated by the following: setting the kinetic energy (equation (V-5)) equal to the stored energy (equation (V-7))

$$\frac{1}{2}\frac{m}{g}V^2 = E_i$$

or

$$V_t^2 = 2g\frac{E_i}{m} \qquad \text{(VII-1)}$$

where V_t = the theoretical snapback velocity

The theoretical velocity is calculated by substituting values for the linear density (m) in Table 6-3 and the Storage Energy from Table 6-1 in the above equation; the results appear in Table 7-6. In all cases the actual snapback velocity is less than the theoretical velocity; the difference ranges between approximately 8%-69%.

TABLE 7-5 COMPARISON OF ADJUSTED SNAPBACK VELOCITIES

		FROM TABLE 6-1				FEYRER (REF 2)			
		Dia.(In)	% BS At Failure	1 Velocity (Ave) (ft/sec)	2 Adjusted Velocity (ft/sec)	Dia.(In)	3 % BS at Failure	4 Velocity (Ave) (ft/sec)	Difference (2)
Nylon	Double Braid	7/8	63.5	505	573	2	82.	604	5%
	8-Strand Plait	7/8	61.0	529	609	2 1/4	81.	604	1%
Polyester	8-Strand Plait	3/4	59.0	358	406	2 1/2	76.	463	7%
Polypropylene	8-Strand Plait	3/4	56.0	418	490	3	77.	394	20%

(1) The Adjusted Velocity (in Column 2) is the velocity (in Column 1) adjusted to the % break strength (BS) in Column 3.

(2) Difference is between the adjusted velocity (column 2) and the velocity in column 4. It is the difference in velocity of two lines (of the same material/construction) of different diameters that fail at the same percent of the break strength.

TABLE 7-6 THEORETICAL SNAPBACK VELOCITIES

		Theoretical Velocity (ft/sec)	Actual (1) Velocity (ft/sec)	Error	R_v	R(2)
Nylon	Double Braid	600	505	.188	.71	.70
	8-Strand Plait.	693	529	.310	.58	.58
	Cross-Lay	556	374	.480	.45	.44
Polyester	Double Braid	610	359	.699	.35	.34
	8-Strand Plait.	390	358	.089	.84	.83
Polypropylene	8-Strand Plait.	518	418	.239	.65	.65
	3-Strand (Staple Fiber)	433	337	.284	.60	.60

R_v: Energy release ratio calculated using the actual and theoretical snapback velocities;
R: Energy release ratio calculated using storage energy and snapback energy.

$$R_v = \frac{(\text{Actual Velocity})^2}{(\text{Theoretical Velocity})^2}$$

(1) From Table 6-1

(2) From Table 7-3

$$\text{Error} = \frac{\text{Theoretical Velocity} - \text{Actual Velocity}}{\text{Actual Velocity}}$$

It is interesting to note that the Energy Release Ratio can also be used to quantify the difference between the theoretical and actual snapback velocities. The Energy Release Ratio (equation (V-6)) is

$$R = \frac{E_s}{E_i} \qquad \text{(V-6)}$$

Snapback Energy (E_S) is given by equation (V-5)

$$E_s = \frac{1}{2}\frac{m}{g}V_A^2$$

where V_A is the actual snapback velocity. Theoretical snapback velocity is calculated from equation (VII-1); therefore,

$$E_i \simeq V_t^2$$

and

$$E_S \simeq V_A^2$$

Substituting both proportionalities into equation (V-6) yields equation (VII-2).

$$R = \frac{V_A^2}{V_t^2} \qquad \text{(VII-2)}$$

Substituting the velocity values from Table 7-6 into equation VII-2 shows that the numerical values of the Energy Release Ratios are the same using energy quantities (as in equation (V-6)) or velocity values (as in equation (VII-2)).

8.0 CONCLUSIONS

a. The bend-over-pin test method employed in this investigation appears adequate for all material/construction combinations except 3-strand twisted line which does not consistently fail completely. The following factors should be controlled carefully to ensure accurate results that are comparable to the results of other investigations.

(1) The Storage Energy should be recorded during the loading over the pin fixture and not assumed to be the same as resulting from a straight pull on a short sample.

(2) The velocity used in the kinetic energy calculations must be clearly defined and consistently used because the velocity varies along the line and that has a great effect on the resulting kinetic energy.

b. Three parameters proposed to quantify snapback behavior, Storage Energy Potential, Snapback Energy Potential, Energy Release Ratio appear to (a) be an effective way to quantify snapback and (b) show reasonable correlation with other available data. They must be derived with care and consistency to enable comparison with other data.

c. Storage Energy Potential: (1) is fundamental to a line material/construction combination and is independent of diameter, (2) varies over a range of approximately 100 percent for the lines tested (i.e. storage energy potential of some lines is twice that of others).

d. Snapback Energy Potential: (1) is only slightly higher in 8-strand plaited line than in double-braid line, (2) is significantly higher in nylon line than in polyester line (double-braid and 8-strand plait construction), (3) is significantly lower in nylon cross-lay and polyester double-braid line than in the other lines tested, in some cases the reduction is as much as 50 percent.

e. Energy Release Ratio: (1) does not show a substantial trend among materials and constructions, (2) is approximately twice as high for some lines as others, (3) is lowest for nylon cross-lay and polyester double-braid line than the other lines tested.

f. Failure Mechanism: (1) cascading appears to reduce the energy released at complete failure, (2) nylon cross-lay line demonstrates a cascading failure mechanism that fails completely in 5 milliseconds which is almost an order of magnitude slower than double-braid and 8-strand plait line, (3) polypropylene 3-strand staple fiber line demonstrates a cascading failure in the last strand that fails after the two strands have failed.

g. The snapback path of a line that fails in clear line (i.e., not bent around a deck fixture) is very narrow; the line does not sweep a large volume as it recoils. A line that retracts around a deck fixture will have a significant lateral velocity and sweep a wide path as it retracts off the fixture.

h. Snapback velocity is: (1) independent of diameter and dependent on tension at failure for a particular material/construction combination, (2) between 8% and 69% lower than the theoretical velocity calculated by setting the Stored Energy equal to the Snapback Energy, (3) not constant over the length of the line. It is highest at the failure point and decreases away from that point.

i. While the results of this investigation are supported by the results from Professor Feyrer, there are areas where the results do not agree. Even though the causes of these discrepancies are not understood at this time, they do underscore the fact that somewhat different test conditions may yield rather different results. The causes of these discrepancies should be studied in detail in an effort to more precisely define the important parameters of the test method and snapback evaluation method.

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APPENDIX A
PHOTOGRAPHIC INSTRUMENTATION

The velocity measurement camera was a Photo-Sonic 1-W camera manufactured by Photo-Sonics. The operating settings were:

Frame rate: 800 frames/sec.
Shutter ratio: 1/20
Shutter speed: 1/16,000 sec.

The film was a fine grain positive film of ASA 400 pushed two stops during development. These conditions produced good quality photographic images with no blur. The camera was obtained from a Naval Air Systems Command, Naval Air Station, Norfolk, Virginia.

The failure zone camera was a Photec 4 manufactured by Photonic Systems, Inc. The operating settings were:

Frame rate: 3000 frames/sec.
Shutter rate: 1/10
Shutter speed: 1/30,000 sec.

Even at 3000 frames per second, the failure of double-braid line was completed in only two frames and the images were so blurred as to be of very little value. The limited film capacity of the camera does not permit using a faster frame rate because, with the variability of synthetic line tensile strengths, the probability of recording the event before the film is out is very low. Synthetic lines that fail at a slower rate than double-braid line are recorded on more frames although some individual strands are blurred because of individual high velocities.

APPENDIX B
EYE SPLICE/BOLLARD TESTS

OBJECTIVES:

As discussed in Section 6.0, a set of tests were necessary to determine if the partial failures observed with the snapback fixture are caused by the small diameter pin of the snapback fixture or if they occur over a bollard of the size that might be used in the field.

TEST SETUP:

The tests were performed by wrapping the test sample 4-6 times around a 10-1/2 inch diameter bollard and tying the end to a cross member of the test machine. The pulling end of the line was attached to the cross head of the test machine with an eye splice that was nine inches long when the legs are together. The eye splice was placed over a 1-3/4 inch diameter clevis pin. Approximately eight feet of clear line was between the bollard fixture and clevis at the beginning of the tests. The lines tested are:

Nylon 3-strand (7/8-inch diameter)
Polypropylene 3-strand monofilament (1-inch diameter)
Polypropylene 3-strand staple fiber (7/8-inch diameter)
Nylon cross-lay (7/8-inch diameter)
Polypropylene 8-strand plaited (3/4-inch diameter)

In addition to 3-strand construction, cross-lay and 8-strand plaited were also tested to confirm the snapback failure modes. The 8-strand plaited line has been observed to partially fail occasionally with two strands remaining to hold the line together. These tests would determine if that happens when the line is used around a bollard rather than loaded with eyesplices in the end.

RESULTS:

1. The failure mode of the samples tested are the same over the snapback pin as it is over the 10-1/2 inch bollard fixture with the exception of nylon 3-strand line.

Table B1-1 displays the failure modes of lines in the three different conditions;

a. Eye/eye: loaded in a straight pull test condition with eye splices in both ends (as in the baseline tensile test).

b. Snapback pin fixture: eye splice in the pulling end of the line with the other end bent around the 1-inch diameter failure pin.

c. Eye splice/bollard: eyesplice in the pulling end and the other end wrapped around the bollard as described in the previous section.

Nylon 3-strand line fails completely in four of six tests in the eye/eye tests, completely in all the eye/bollard tests, but fails partially in all the snapback fixture tests.

2. The strength of the line around the bollard is the same as a line with an eye splice in both ends except for nylon cross-lay which is 20.3% stronger in the bollard tests. Results in Table B1-2 show that the lines failed at both the splices and in clear line near the bollard. This tendency toward random failure and the fact that the tensile strengths are the same in both test conditions, tend to suggest that the eye splices are achieving 100% of the strength of the line.

3. The lines generally fail in clear line approximately 1-2 feet from the bollard. At the beginning of each test the line was loaded to $2000D^2$ and a mark made on the line approximately one foot behind the tangent point of the line on the bollard, (i.e., one foot around the first wrap of the line). As load is applied to the line and it stretches, that mark is drawn off the bollard and is in general 1-2 feet away from the bollard at failure. Generally, failure occurs between the mark and the tangent point on the bollard. In the case of polypropylene line in particular, some melting is observed between the mark and the tangent point and failure does occur in that area. However, since the strength of the polypropylene line is not affected, it does not appear that the surficial damage had any effect on the tests.

TABLE B1-1 FAILURE TYPES

	eye/eye	Snapback pin fixture	eye/bollard
Nylon double-braid	C	C	--
8-plait	C	C	--
3-strand	C(4,2)	P	C
Cross-Lay	C	C	C
Polyester Double-Braid	C	C	--
8-plait	C	C	--
3-strand	P	P	--
Polypropylene 8-plait	C	C	C
3-strand	P	P	P
3-strand staple fiber	P	P(2, 7)	P

C: Complete failure
P: Partial failure
(x,y): x = number of complete failures
y = number of partial failures

TABLE B1-2 TEST RESULTS

		Tensile Strength					
		Eye/Eye	Eye/Bollard	%	F-Test	t - Test	Conclusion
Nylon	3-Strand	19932 (1201)	18413 (813) I II	-7.6	$df_1=1$ $df_2=2$ $F=2.18$ $F(.90,1,2)=8.53$	$t=1.81$ $df=4$ $t(4,.90)=2.13$	(1) Same
	Cross-Lay	21101 (2566)	25403 (959) I II	+20.3	$df_1=2$ $df_2=2$ $F=7.10$ $F(.90,2,2)=9.00$	$t=2.72$ $df=4$ $t(4,.90)=2.13$	(2) Different
Polypro-pylene	8-Strand Plait	8567 (762)	9131 (318) II	+6.5	$df_1=2$ $df_2=1$ $F=5.79$ $F(.90,2,1)=49.5$	$t=.95$ $df=3$ $t(3,.90)=2.35$	(1) Same
	3-Strand Monofilament	9939 (310)	11161 (965) III	+12.2	$df_1=2$ $df_2=2$ $F=9.69$ $F(.90,2,2)=9.00$	$t=2.09$ $df=4$ $t(4,.90)=2.13$	(1) Same
	3-Strand Staple Fiber	13077 (1275)	11607 (283) III	-11.2	$df_1=1$ $df_2=3$ $F=20.30$ $F(.90,1,3)=5.54$	$t=1.03$ $df=4$ $t(4,.90)=2.13$	(3)

(1) Within 90% confidence limit, there is no statistically significant difference between the tensile strength in the eye/eye and the eye/bollard tests.
(2) Within 90% confidence limit, there is a statistically significant difference between the tensile strength in the eye/eye and the eye/bollard tests.
(3) The results of the statistical tests are not conclusive.
( ) Standard deviation.

Tally mark in eye/bollard tensile strength indicate: Failure at eye splice if it appears in left of box.
Failure in line near bollard if it appears in right of box